# TPF Briefing to the ORIGINS Subcommittee

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June 7, 2002

# Agenda

- TPF Status Overview
- Architecture Concept Selection
- StarLight Status
- Pre-Formulation Planning

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# TPF Status- Overview

- Pre-Formulation Architecture Studies
  - Received final reports, integrated models and technology roadmaps from all four study teams
  - Architectures for further study and development have been selected
    - Visible coronagraph and nulling IR interferometer (connected and separated spacecraft
    - Project Briefed HQ
  - Contracts have been extended to complete comprehensive study report
    - Draft Report in Review
    - Study Teams will be dissolved at the end of the contracts
- Re-planning
  - In the process of consolidating the Starlight effort with TPF
    - The Starlight team primary focus will be to provide a ground demonstration of the technology required for the formation flying interferometer version of TPF
  - Formalizing coordination with ESA’s DARWIN Mission
    - Draft LOA in review at State Department

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# TPF Status- Overview (Cont.)

- Technology
  - Continuing to work on TPF Technology Plan including the Starlight activities
    - Plan due end of this FY
  - Several major Starlight technology milestones achieved
  - Mid-IR nulling testbeds in operation at JPL (in collaboration with Keck)
  - Advanced Cryocooler Technology Development Program is underway
    - Four teams are on contract and kickoff meetings have been held
  - High Dynamic Range Imaging Testbed coming together at JPL
  - Second major technology development procurement is in preparation for 2m class coronagraph mirror demonstrator
  - Industry led system level TPF technology procurement and university/small business targeted TPF R&D procurement planned for later this year with funding in early FY2003
- Science
  - Completed, published and briefed HQ on Bio-Marker Studies
  - Exo-Planet NRA selections made and contracts in place
  - Released TPF related addition to ROSS NRA call
  - Current SWG to be dissolved shortly;
    - Dear Colleague Letter will be sent out by HQ (7/1) for new Science Team

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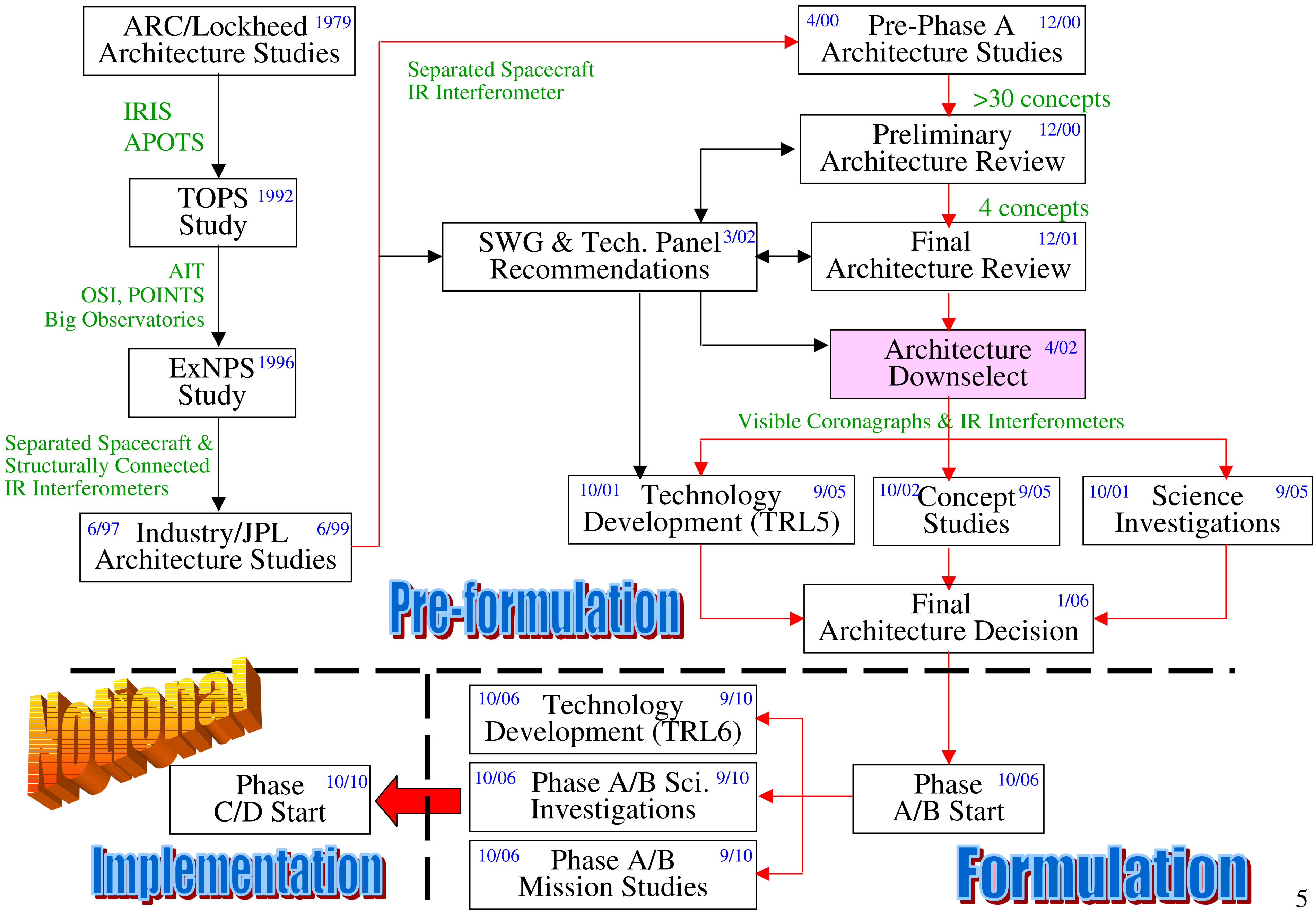
# TPF Architecture Selection Process



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# Architecture Selection Criteria

- Science capability
  - Detect radiation from earth-like planets in the habitable zone
  - Characterize orbital & physical properties
  - Characterize atmospheres & search for bio-markers
  - Provide broader understanding of all planetary system constituents (giant planets, debris disks, etc.)
  - Provide advanced capability for astrophysics at minimal extra cost
- Technological maturity
  - Understanding of the technology challenges
  - Degree of difficulty with respect to the current state of the art and anticipated technology inheritance from prior missions (eg, NGST, SIRTF, SIM)
  - Likelihood of meeting technology development goals by 2005 for the available budget
- Programmatic
  - Relative cost and risk
  - Relevance to future observatories providing ultra-high spatial resolution capability

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# Key Science Requirements

- Sky coverage: 60%
- Mission duration:  5 years
- Science program:
  - Primary objective is planet detection and characterization
  - Secondary general astrophysics
- Planet Finding/Characterization:
  - Nominal planet is defined as solid body with Earth radius at 1 AU, T=270 K. Assume exo-zodiacal dust will be 1-10x the solar system level.
  - Number of stars (F5-K5) surveyed for planets (R=3, SNR=5): 150
- Astrophysics:
  - Carry out program of high resolution imaging at minimal extra cost to the mission (reduced in scope relative to initial Architecture Study SOW)

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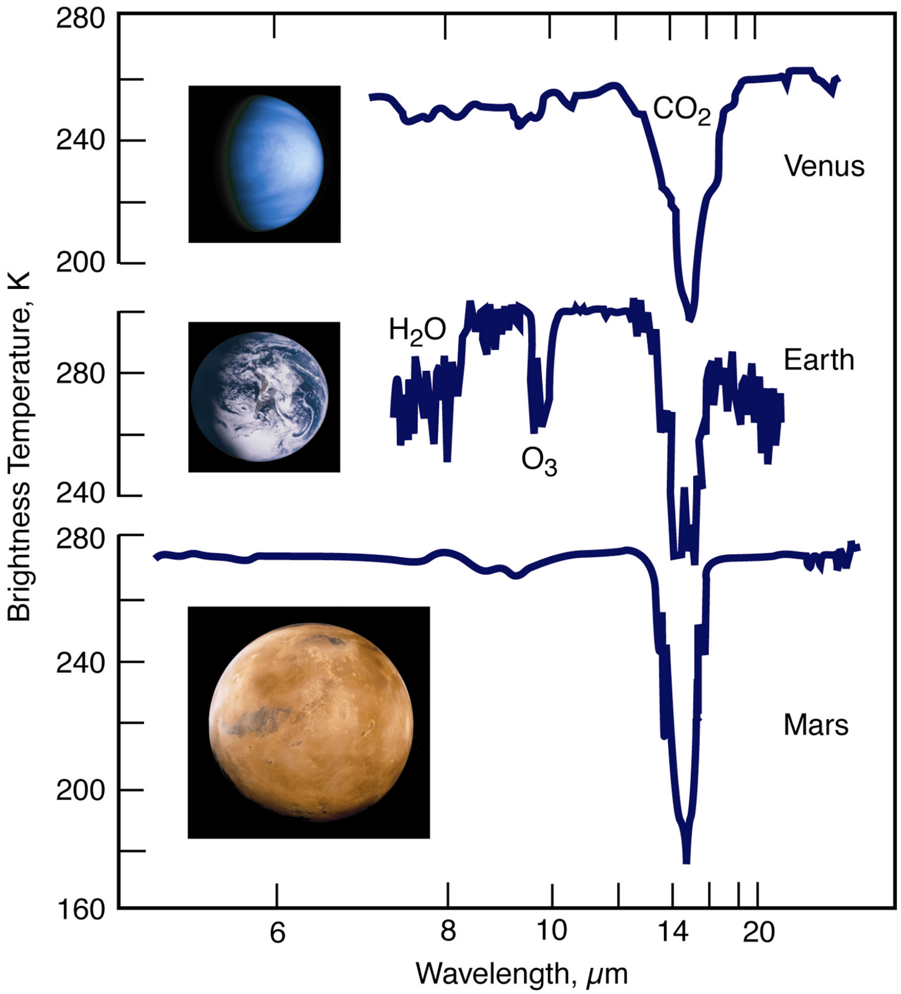
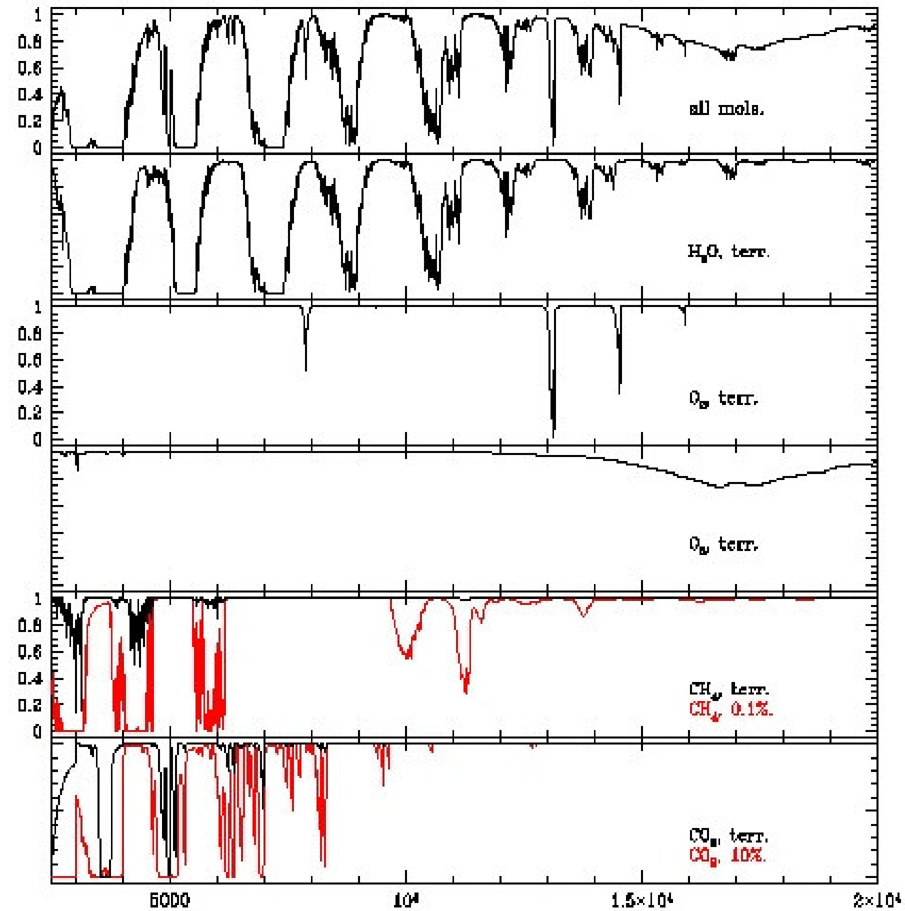
# The Appearance of Distant Earths

- TPF-SWG (Des Marais et al.), Wolstencroft & Raven (2000) and NAI team (Meadows) have addressed appearance of Earths
- Both mid-IR and near-IR/visible contain important diagnostics



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# Architectures Evaluated in Phase 1 Study

| Architecture Families | # | Architecture Families | # |
|---|---|---|---|
| ***Lockheed Martin*** | | ***Ball*** | |
| Free Flying Interferometers | 4 | Coronagraphs: including Spergel-Kasdin Pupil, Masking, Phase Mask | **7** |
| Fizeau Interferometer | 1 | Occulting Screens | **2** |
| Connected Interferometers | 3 | Nulling Interferometers | **10** |
| Tethered Interferometers | 1 | Hypertelescope | **2** |
| Coronagraphs | 1 | | |
| ***TRW*** | | ***Boeing-SVS*** | |
| Large Aperture Coronagraph | 3 | Coronagraphs | **7** |
| Fresnel Coronagraph w/free flying elements | 1 | Hypertelescope: including Snapshot Imaging Array, Linear Array | **3** |
| 100 m sparse aperture | 1 | Interferometers: Separated Spacecraft, & Connected Structure | **3** |
| Free Flying Occulter | 1 | Laser Trapped Mirror | **1** |
| Interferometers: Connected and Separated Spacecraft | 8 | | |

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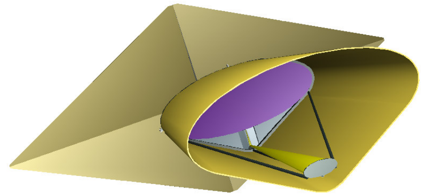
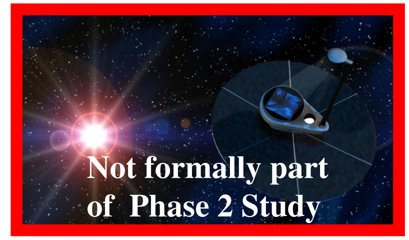
# Architectures Evaluated in Phase 2 Study

## Visible Coronagraphs

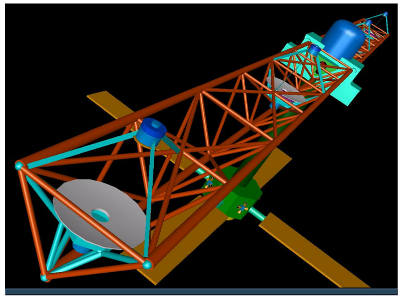


Variable Pupil Visible Coronagraph (Ball)

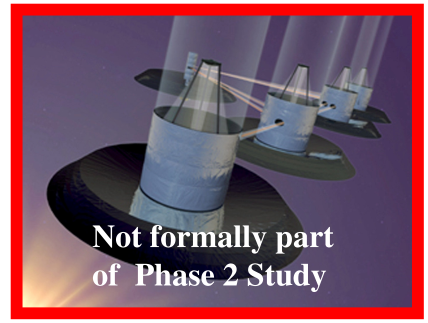



Apodized Square Aperture (Boeing-SVS)

## IR Interferometers

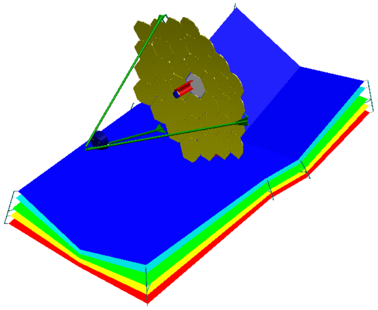


Structurally Connected IR Interferometer (LMMS)

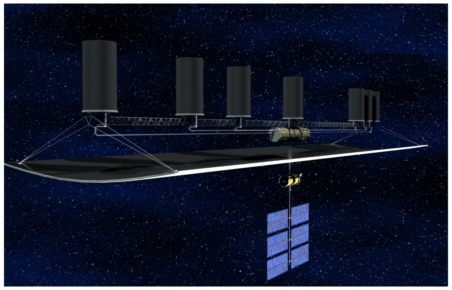



Separated Spacecraft IR Interferometer (Book)

## Other Concepts



Large Aperture IR Coronagraph (TRW)



Non-Redundant Linear Array Hypertelescope (Boeing-SVS)

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# Candidate Architecture Characteristics

| | Aperture/ Baseline | WFE /Optical Path Error | Precision Deployment | Other |
|---|---|---|---|---|
| **Ball Spergel Visible Coronagraph** | 4x10m elliptical monolith; 300 PM actuators; apodized pupil | -1 -5nm rms manuf.; -1nm rms corrected; 0.3Å rms stability; | Telescope structure | Telescope rotates in L2 or drift-away orbit |
| **Boeing-SVS ASA Visible Coronagraph** | 8x8m square segmented; TBD PM actuators; apodized pupil | -3 -6nm rms manuf.; -1nm corrected; few Å rms stability; | Telescope structure and primary mirror | Assembly in orbit- then to L2 |
| **TRW IR Coronagraph** | 28m diameter segmented; 13 PM actuators per segment | 500nm rms manuf.; -30nm rms corrected -1 µm rms stability | Telescope structure and primary mirror | L2 orbit; T=21K |
| **LMMS Structurally Connected IR Interferometer** | 9,21,40m baselines; 2x0.6m, 4x1.7m, 4x3.5m collectors respectively | <100nm rms WFE; 7.2nm,10.6nm,10.6nm Optical path error (for 9,21,40m respectively) | Truss for 21 & 40m versions | Baseline rotates; L2 orbit; T=60K, 40K, 40K (for 9,21,40m respectively) |
| **"Book Concept" Separated S/C IRInterferometer** | 4x3.5m collectors; 1km baseline | <100nm rms WFE; 3nm OPE | none | FF Baseline rotates; L2 orbit; T=40K |
| **Boeing-SVS IR Non-Redundant Linear Array** | 7x3m collectors; 100m baseline; | $\lambda$/200 rms WFE (40nm@ 8µm); 72nm OPE | 100m truss | Baseline rotates; LEO assembly in orbit then to L2; T=100K |

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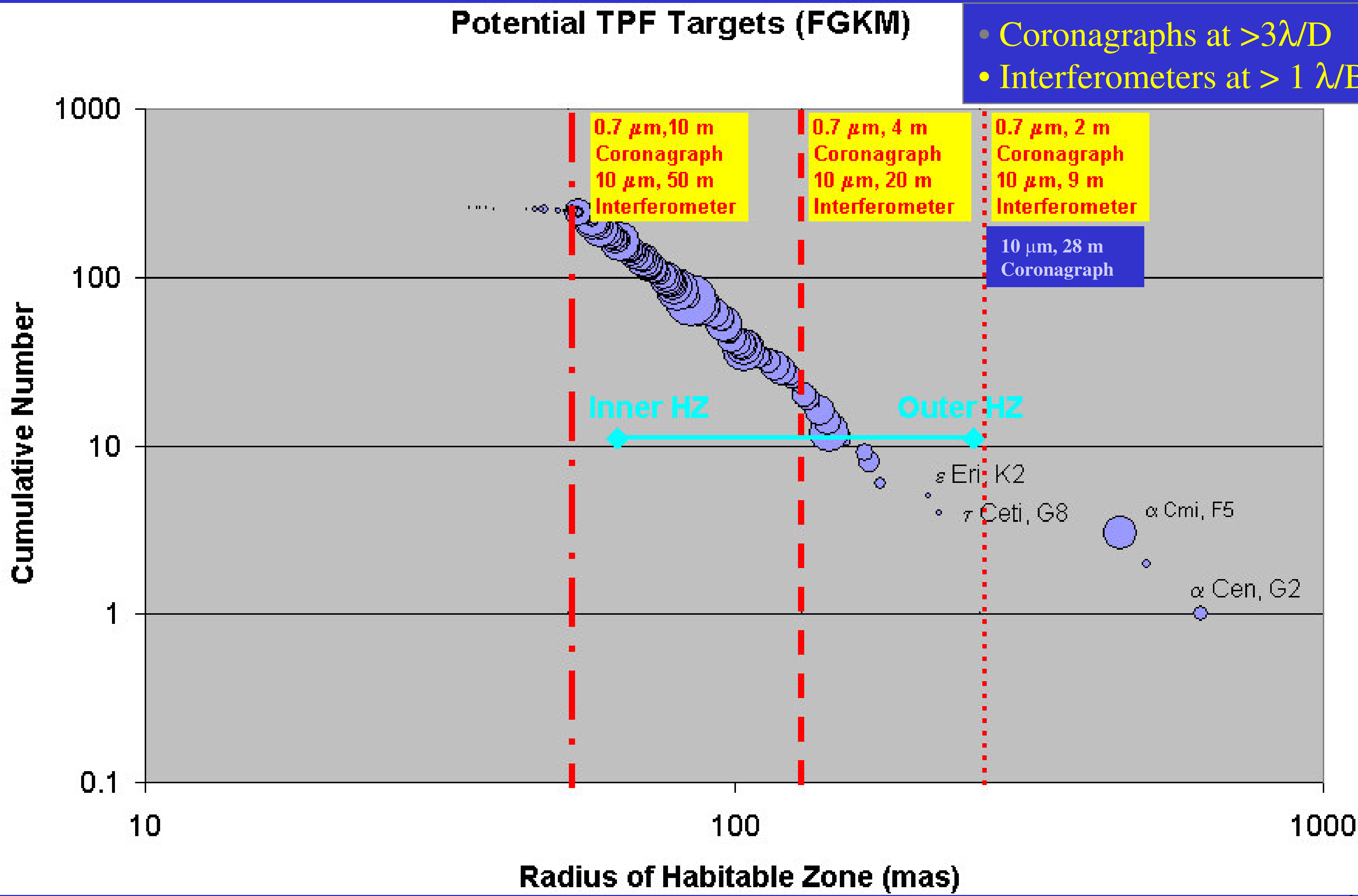
# The Challenge of Angular Resolution

- Coronagraphs at >3λ/D
- Interferometers at > 1 λ/B



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# Detect and Characterize Earth at 10 pc

| Architecture | Time to Detect Earth Twin (SNR=5) | Time to Detect Planet's Atmosphere | Time to Detect Oxygen or Ozone |
|---|---|---|---|
| Apodized Square Aperture (ASA) | 6.3 hr (incl. 2 rotations) | 1 d ($H_2O$) R=20,SNR=5 | 3.8 d ($O_3$) R=20,SNR=5 |
| Non-Redundant Linear Array (NRLA) | 2.5 hr (one half rotation) | 2.7 d ($CO_2$) R=10,SNR=5 | 2.1 d ($O_3$) R=20,SNR=5 |
| BASD Coronagraph | 0.86 hr (incl. 2 rotations) | 0.14 d ($H_2O$) R=24,SNR=5 | 0.8 d ($O_2$) R=70,SNR=5 |
| BASD Shaped Pupil | 5.3 hr (incl. 9 rotations) | 0.09 d ($H_2O$) R=24,SNR=5 $\leq$ 10 pc | 0.7 d ($O_2$) R=70,SNR=5 $\leq$ 10 pc |
| LMSS Structurally Connected Interferometer (40m) | 2 hr (but min 6hr 1 full rotation) | 0.8 d ($H_2O$, $CO_2$, $O_3$) R=20, SNR=5 | |
| Separated Spacecraft Interferometer (Book) | 2 hr (but min 6hr 1 full rotation) | 0.6 d ($H_2O$, $CO_2$, $O_3$) R=20, SNR=5 | |

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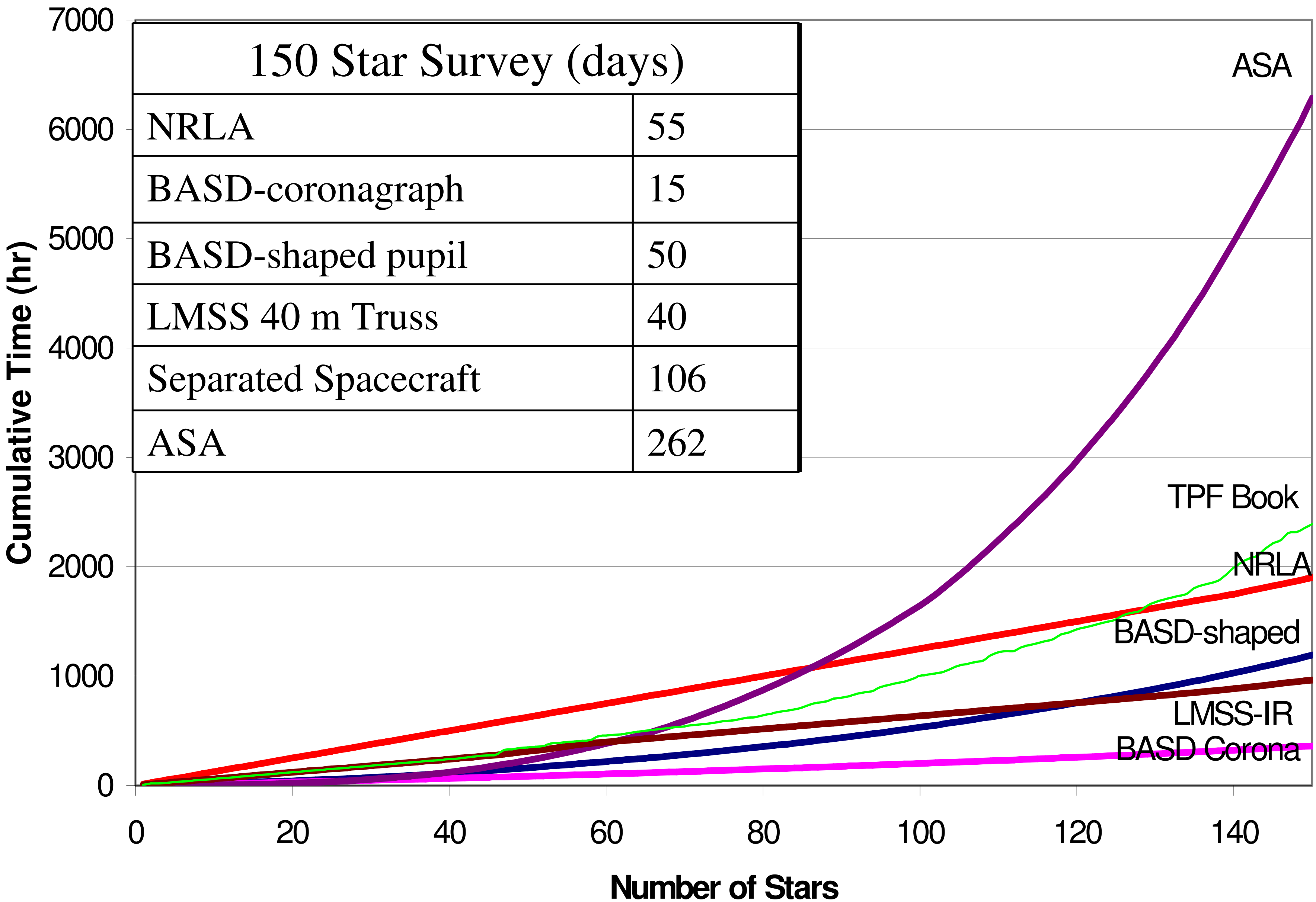
# Time To Survey 150 Stars (1 Epoch)

| 150 Star Survey (days) | |
|---|---|
| NRLA | 55 |
| BASD-coronagraph | 15 |
| BASD-shaped pupil | 50 |
| LMSS 40 m Truss | 40 |
| Separated Spacecraft | 106 |
| ASA | 262 |



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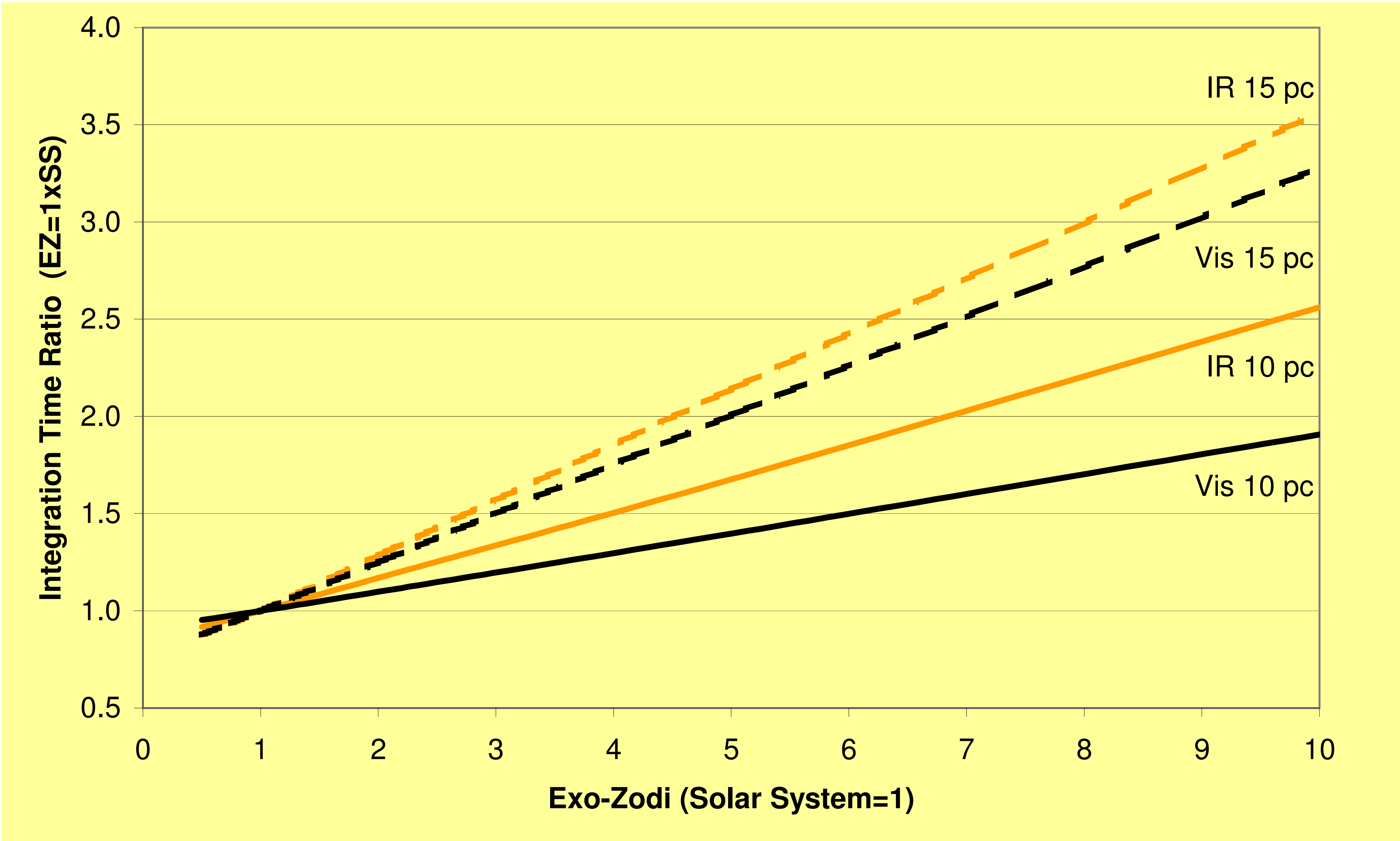
# Exo-Zodiacal Emission Affects Both Visible and IR



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# Conclusions & Recommendations from the TPF-SWG

- Both the IR and the visible regions of the spectrum offer critical information on planets, their atmospheres and bio-markers and both should be pursued. Technology, not science will likely be the driver to determine which will be pursued first.
- Differentiating between the architecture alternatives will require
  - scientific insight to refine planet detection requirements
  - understanding of the real-world limitations of each architecture
  - support of technology development for both until a clear choice between them is quantitatively apparent
- Two classes of architectures are recommended for further study and technology development.
  - Visible light coronagraphs/apodized aperture systems
  - IR nulling interferometer systems- both separated spacecraft & structurally connected versions
- Reduced scale systems (relative to the full TPF) should also be studied further
  - Such systems (both architectures) are likely possible in the nearer-term
  - Project should evaluate benefits in cost, schedule and technology risk reduction against reduced science capabilities

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# Conclusions and Recommendations of TPF Technology Review Panel

- TPF has two primary system architecture alternatives which should be pursued.  The nature of the risk is different for the two.
- IR nulling interferometers
  - Biggest technical risk is system complexity
    - e.g.,  multi-level control, cryogenic operation,
  - Individual components and subsystems are less challenging than the system
    - Draws heavily on SIM, SIRTF and NGST
  - "Super large" (≥40m) structurally connected systems are a major risk and are not recommended for further consideration
    - However, ≤25m structures for a near term reduced scale system are largely an engineering challenge, not a technology challenge
- Visible coronagraphs.
  - Biggest technical risks are developing components/subsystems meeting requirements
    - e.g., mirror manufacturing and ≤Å level WFE stability is extremely challenging
  - System level operation is less challenging than the development and manufacture of the individual components/subsystems
    - Direct imaging, functionally simple

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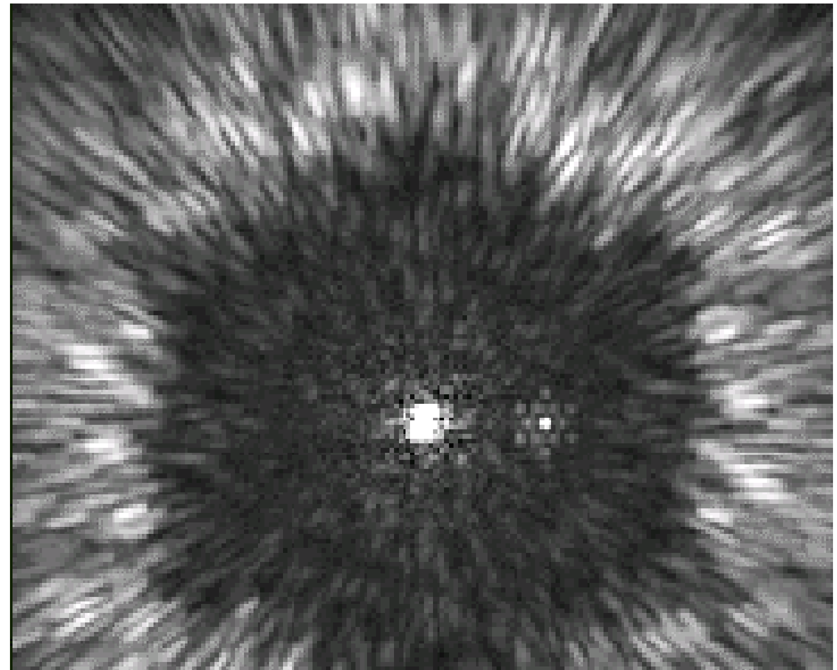
# JPL Architecture Selection Decision

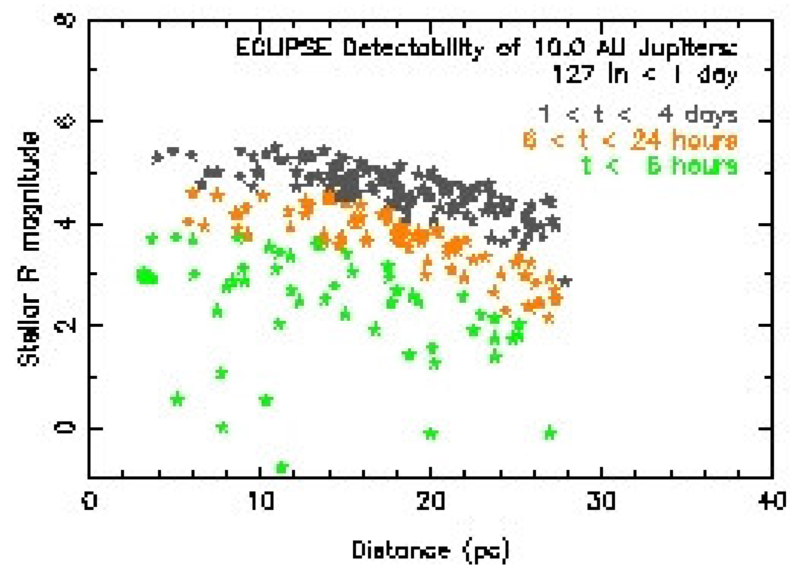
- Study and develop technology for:
  - visible coronagraphs/apodized aperture systems
    - up to 8-10m aperture systems to do the full TPF science
    - smaller aperture systems as potential nearer term missions
  - IR nulling interferometer systems
    - separated spacecraft version to do the full TPF science
    - shorter baseline structurally connected IR interferometers as potential nearer term missions
- Evaluate reduced scale missions
  - determine cost, schedule and technology risk reduction
  - determine capability to address TPF science questions

# Steps to Visible Light TPF

- Near term, direct visible imaging with coronagraphs
  - Simple coronagraphs in near IR with NGST for closest stars and for hot, young Jupiters in 5 µm window
  - Advanced coronagraph/apodized 1-2 apertures in visible (MIDEX, Discovery)
    - → 4 m ("TPF-Lite" offramp)
    - → 8~10 m apertures (TPF)
- Properties of Giant Planets
  - –Radius$^2$*albedo($\lambda$)*$\Phi$(t)
  - –Atmospheric composition
  - –Rotation →surface/atmospheric variability
- Detection of nearest earths
- Workshop to address ground/space trade
  - –What could 30-50-100(!) m telescope do?



*NGST coronagraphic image of a planet around Lalande 21185 (M2Vat 2.5pc) at 4.6 µm*



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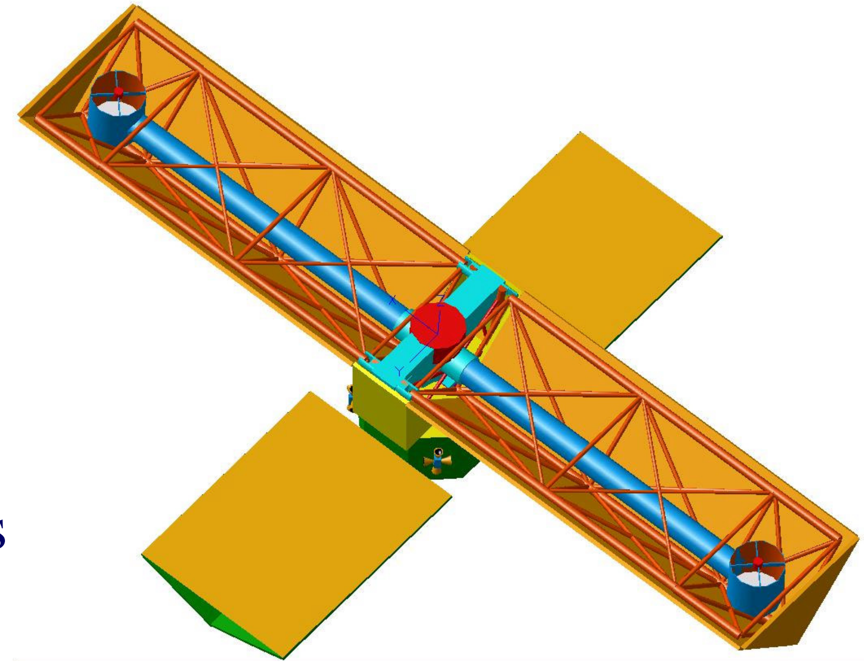
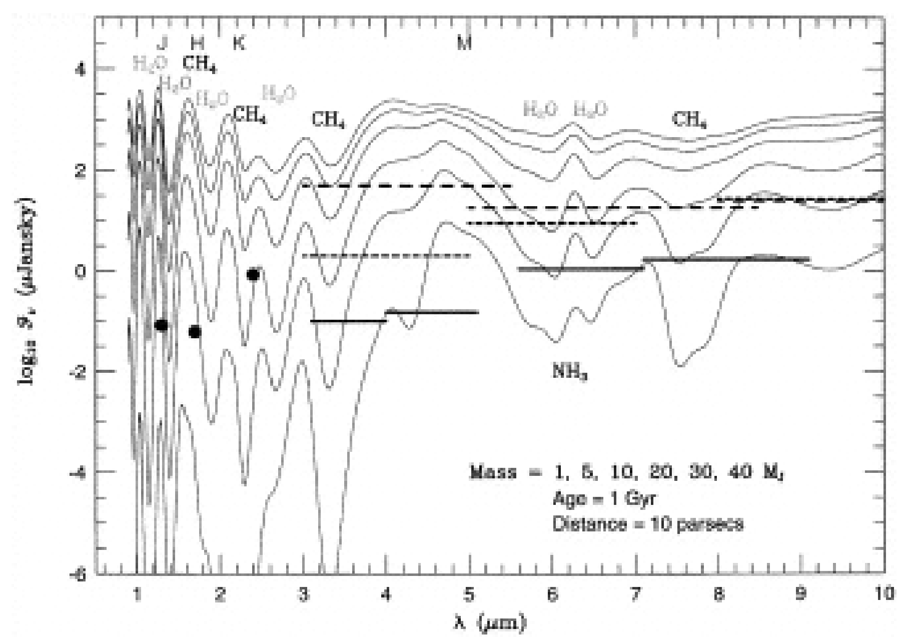
# Steps to a Mid-IR TPF



- A precursor mid-IR nulling interferometer with two 0.6 m telescopes on a 10 m boom could detect hot, young Jupiters out to > 50 pc
- A larger precursor with 1-2 m mirrors on a 20 m boom could detect Jupiters within 25 pc and Earths within 8 pc
- Properties of Giant Planets
  - Radius and temperature
  - Atmospheric composition
- Orbital properties, radius and temperature of nearest Earths
- Extension of available technology
  - *"TPF-Lite" Offramp =SIM- pico+ cryo*



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# StarLight Status- Overview

- New Guidelines
  - StarLight received direction from NASA Code S on 3/1/02 to:
    - Cease flight aspects of development
    - Focus on ground demonstration of technologies that support the formation-flying interferometer concept for TPF

- Redirection of FY02 Activities:
  - FY02 Replan complete
  - Workforce transition nearly complete – technologists retained, flight engineers successfully transitioned to other projects
  - Ball contract revised consistent with new charter
  - Flight design archive nearly complete

- Technology Milestones proceeding well
  - Formation Interferometer Testbed (fringe tracking)
  - Metrology technologies
  - AFF Prototype (Autonomous Formation Flying Sensor)
  - Formation Flying algorithm development and simulation

- Draft technology implementation plan for FY03-FY05

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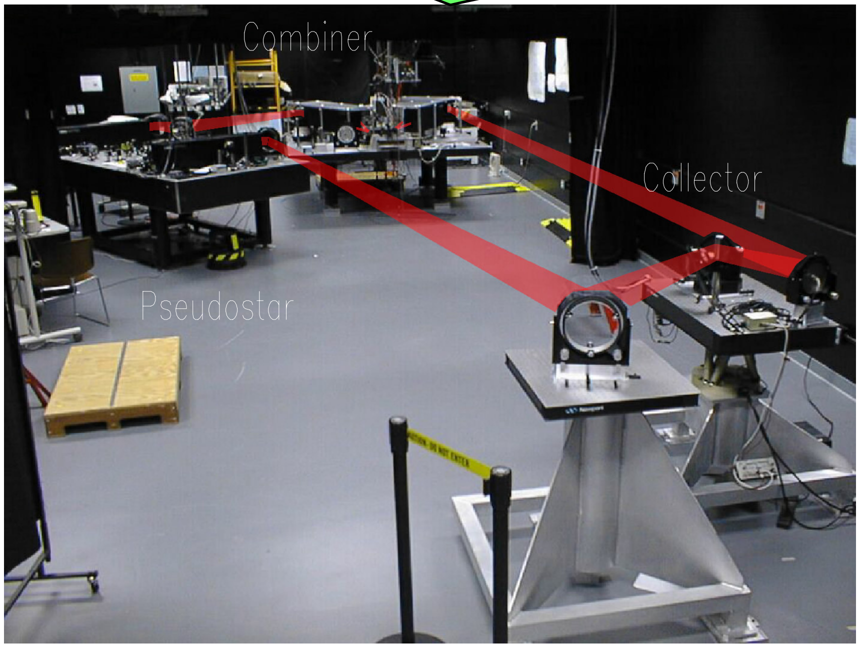
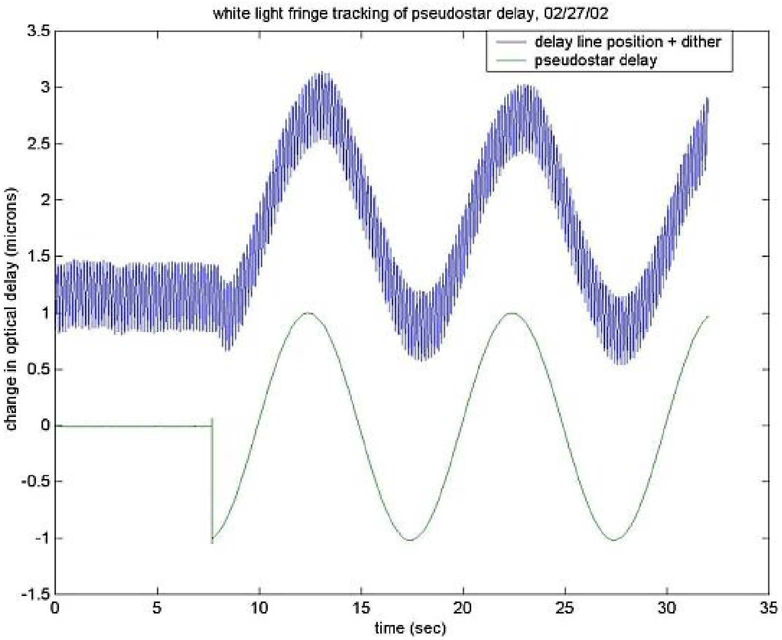
# Fringe Tracking Demonstrated in FIT




FIT = Formation Interferometer Testbed




- White light fringes tracking demonstrated 2/27/2002
  - Instrument visibility 45% (matches the predicted value)
  - All control loops operating
  - Loops tracked for 20 min until deliberately broken (reqt was 10 sec)

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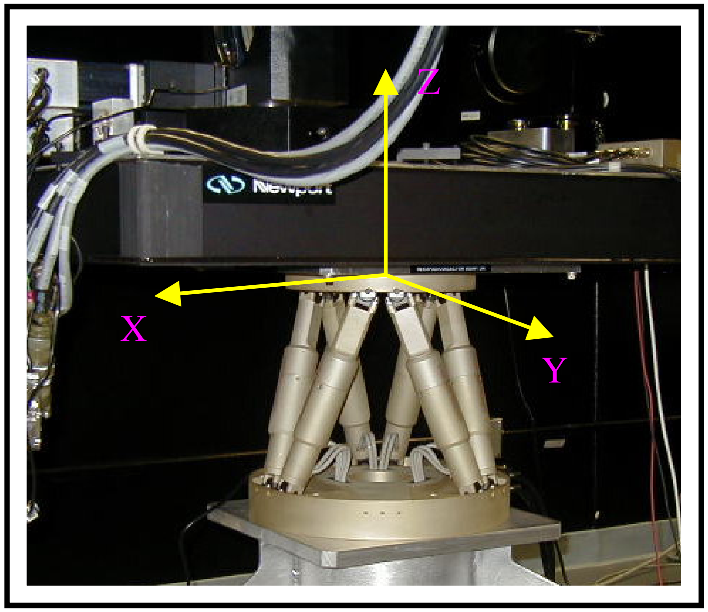
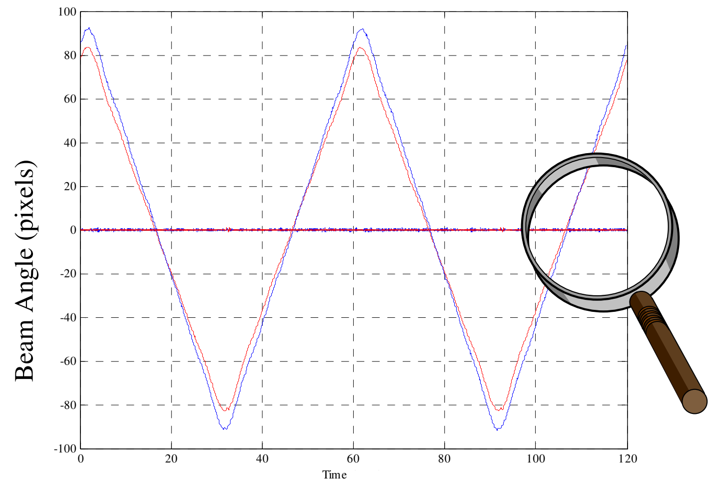
# FIT Closed Loop Control – Moving Collector

PI M-850 Hexapod

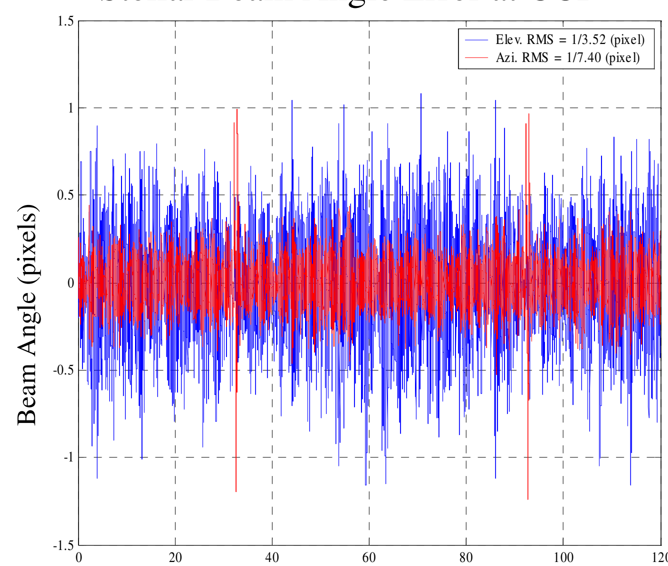



- StarLight and Metrology Loops closed
- Collector moved through representative spacecraft motions
- Loops remain locked at 1/3 pixel (1 arcsec) stability
- Further improvement to 1/5 pixel required for final fringe tracking milestone

Stellar Beam Angle at CCD Due to Collector Coarse Stage Motion




Stellar Beam Angle Error at CCD




Time (seconds)

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# StarLight Planning

- New StarLight charter:
  - Deliver by September 2005 a ground demonstration of formation-flying interferometry technologies to influence the TPF architecture decision
- Ground demonstration of system technologies will include:
  - A set of testbeds and system engineering
  - Targeted component technology development
  - Parallel development of interferometer point designs for TPF
- StarLight will:
  - Submit a preliminary plan for peer review in June 2002
  - Write a joint task plan with TPF and submit a final plan for FY03-FY05
  - Hold a FY02 year-end technology presentation of what's been accomplished
  - Merge with, and become a supporting task to, TPF on October 1 2002 under a single UPN.

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# TPF Pre-Formulation Plans

- Over the period FY2002-FY2005, TPF will perform a series of activities focused on selection a final architecture no later than FY2006 to support a new start in FY2007
- The Project will pursue science, technology and system studies associated with the two selected architectures
  - Science: $4M-$5M/year of competed R&A and fellowships for TPF foundation science
  - Technology: in-house efforts where JPL has special expertise; major competed outside system efforts; university/small business R&D
  - System studies: in house development of a range of point designs
- NASA will coordinate with ESA with the goal of achieving consensus on the best architecture for a joint planet finding mission

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# Recommendations on Technology Development Approach- Per Technology Review Panel

- Recommend comprehensive set of laboratory breadboards and testbeds to validate system designs and models and to reveal unknowns
    - Two-beam system level interferometer to demonstrate planet detectability and predictability from an end-to-end basis.
    - Large-scale formation-flying testbed, e.g., a flat-floor facility to simulate much of formation flying technology
    - Large coronagraph optical optical train to demonstrate Å-level WF quality and passive stability, mirror producibility and model validity.
- Parallel development of integrated models.
- Coordination with Precursor Science and Technology Missions
    - "Eclipse"..or alternate concept….coronagraphy
    - SIM….structural stability, in-space structurally connected interferometry,
    - NGST, SIRTF…cryogenic mirrors, mechanisms, structures, sunshades
    - Keck, LBTI, et al….science and physical phenomena
- Technology flight demonstrations only if laboratory testbeds cannot conclusively resolve uncertainties

# Prioritized TPF Technology Development Plan Content

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| Technology | Visible Coronagraphs | IR Interferometers | | |
|---|---|---|---|---|
| | | Core | Separated S/C | Structurally Connected |
| Nulling | | 1 | | |
| Cryocooler | | 1 | | |
| Cryogenic Opto-Mechanics | | 2 | | |
| High Contrast Imaging | 1 | | | |
| Wavefront Sensing & Control | 1 | 3 | | |
| Large Optics | 1 | 3 | | |
| Formation Flying | | | 1 | |
| Precision Deployable Structures | 3 | | | 3 |
| Low Thrust Propulsion | 2 | 1 | | |
| Metrology | 2 | 2 | | |
| System/Subsystem Testbeds | 1 | 1 | | |
| Integrated Modeling | 2 | 2 | | |

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# System Level Technology

- Planned testbeds and breadboards
  - Interferometers
    - Cryogenic IR nulling and beam train breadboards
    - IR interferometer system testbed
      - Metrology
      - Structure
    - Cryocoolers
    - Separated spacecraft interferometer testbed (FIT+)
    - Formation flying testbeds
      - Formation control
      - Formation sensing
      - SPHERES
  - Coronagraphs
    - High contrast imaging testbed
    - High actuator density deformable mirror breadboards
    - Large visible optics
    - Visible coronagraph system testbed

Planned out-of-house

Planned at JPL

# TPF Schedule

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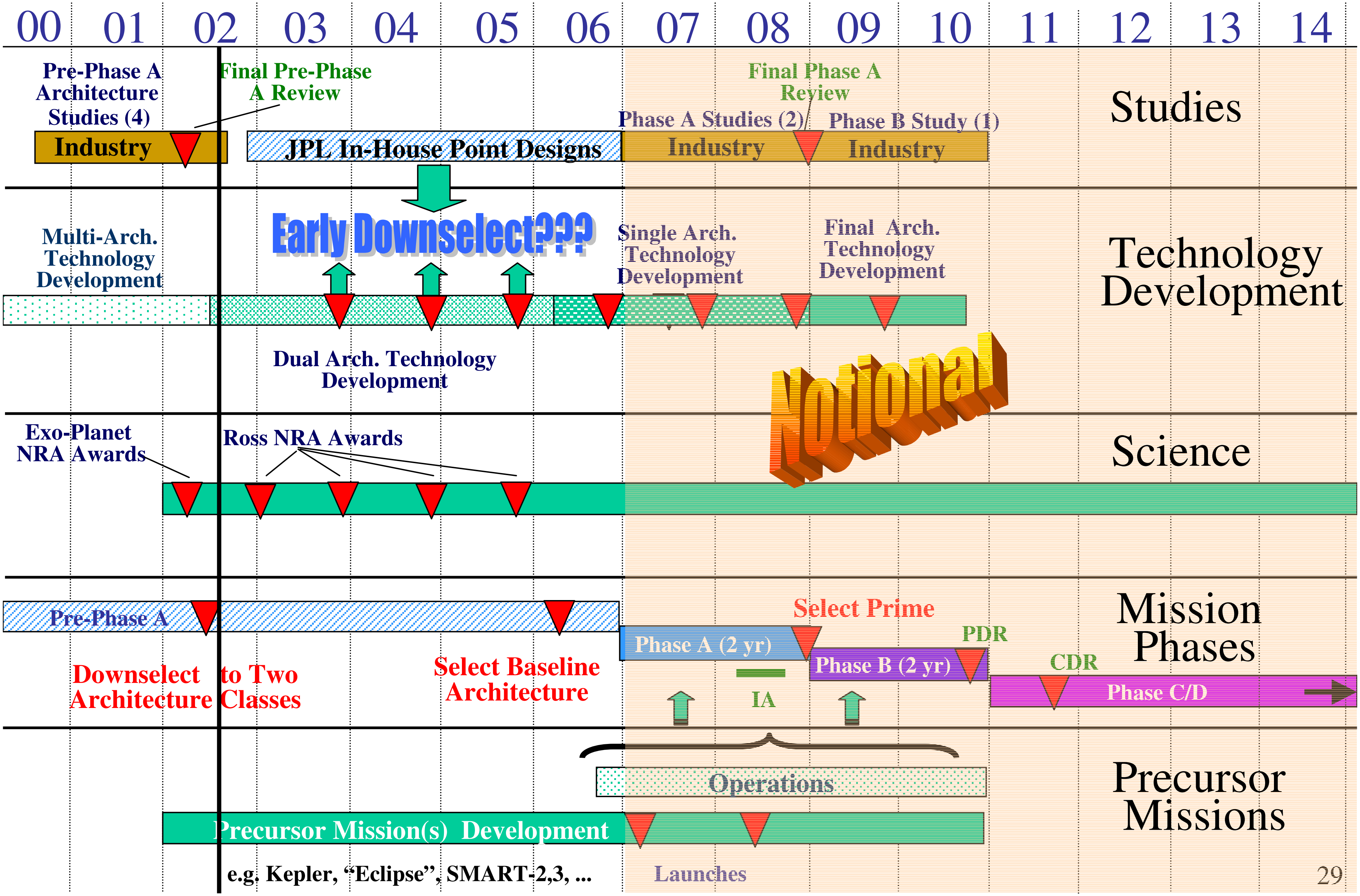

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# Conclusion

- Visible coronagraphs and IR nulling interferometers have been selected as candidate architectures for further study and development
- The TPF Project will pursue science, technology and system studies associated with these architectures
  - Science: significant competed outside R&A for TPF foundation science
  - Technology: in-house efforts where JPL has special expertise; major competed outside efforts
  - System studies: in house development of a range of point designs
- Annual reviews of science, technology, and point design progress will be held to judge readiness for selection of TPF architecture
- TPF will coordinate with the ESA DARWIN Study
  - Science Team participation
  - Technical Interchange Meetings
  - Management team coordination meetings
  - Pre-formulation products
    - Jointly agreed upon architecture decision
    - Formulation phase technology development strategy
    - Formulation phase Letter of Agreement

# Backup Charts

# Major Strengths & Weaknesses: Visible Coronagraphs

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| Strengths | Weaknesses |
|---|---|
| **BALL**<br>• High Q*≈1; Less affected by zodiacal background<br>• Direct imaging; functionally simple; 'Rapid' single mode data collection<br>• Ambient temperature<br>• Testable<br>• Large visible telescope capability for ancillary astrophysics | **BALL**<br>• 4x10m monolithic lightweight primary mirror required<br>• Extraordinary wavefront accuracy needed<br>– Sub-Å WF quality for multi-hour durations<br>• Requires high contrast starlight suppression<br>• Not extendable to future ultra-high resolution observatories |
| • **BOEING-SVS**<br>• Less demanding wavefront accuracy needed (at expense of Q)<br>• Direct imaging; functionally simple; 'Rapid' single mode data collection<br>• Ambient temperature<br>• Testable<br>• Large visible telescope capability for ancillary astrophysics | **BOEING-SVS**<br>• Q<1 implies stringent stability requirements Requires high contrast starlight suppression<br>• 8x8m square lightweight deployable segmented primary mirror<br>• Passive sub-Å WF quality for multi-hour durations<br>• Not extendable to future ultra-high resolution observatories |

*The parameter 'Q' is the ratio of planet flux (light) in the pixel to the background flux in the pixel. It is a measure of signal detectability. Low Q (<<1) implies greater stability requirements to keep scattered/diffracted background stable to required background rejection. Wavefront stability during integration ~$\sigma$/Q, 30 nm/$10^4$~3 picometer

# Major Strengths & Weaknesses: IR Coronagraph

Dan Coulter
Chas Beichman
June 7, 2002

| Strengths | Weaknesses |
| --- | --- |
| **TRW Concept**<br>• Relaxed PM and other optical tolerances relative to visible systems<br>• Direct imaging, functionally simple<br>• Classical coronagraph architecture, functionally well understood<br>• NGST linkage<br>• Large IR telescope capability for ancillary astrophysics | **TRW Concept**<br>• Q<<1 implies stringent stability requirements on telescope<br>• Poor resolution ($\lambda$/D 20X that of visible systems)<br>• 28m Segmented cryogenic primary mirror<br>• Complicated deployment<br>• Post-deployment mechanical stability concerns<br>• 21K operating temperature<br>• Poor overall testability<br>• Not easily extendable to future ultra-high resolution observatories |

*The parameter 'Q' is the ratio of planet flux (light) in the pixel to the background flux in the pixel. It is a measure of signal detectability. Low Q (<<1) implies greater stability requirements to keep scattered/diffracted background stable to required background rejection. Wavefront stability during integration ~$\sigma$/Q, 30 nm/$10^4$~3 picometer

# Major Strengths & Weaknesses: IR Interferometers (Structurally Connected)

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June 7, 2002

<table>
<tr><th>Strengths</th><th>Weaknesses</th></tr>
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**LMMS**

- Modest size 1.7m collector telescopes
  - 3.5m optics for 40m version
  - Use SIRTF or NGST technology for lightweight optics
- Exploits existing and continuing technology
  - SIM, Palomar, Keck, MMT, LBTI, SIRTF, NGST
- Minimal component-level concerns
- Structurally connected design simplifies line of sight rotation mechanics relative to separated s/c version

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**LMMS**

- Reduced science capability
  - ≥40m version required for TPF planet finding
- Fixed baseline
  - Eliminates capability to tune the baseline to maximize contrast ratio and/or spectral throughput
- 40K operating temperature
- Testing and verification complexity
- System and operational complexity
- Not extendable to future ultra-high resolution observatories

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# Major Strengths & Weaknesses: IR Interferometers (Separated S/C)

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| Strengths | Weaknesses |
|---|---|
| **<u>"Book" Concept</u>**<br>• Maximized science capability<br>– Provides very high resolution imaging capability<br>• Variable baseline can optimize contrast ratio and/or spectral throughput<br>• Reconfigurable, highly resilient architecture<br>• Modest size (3.5m) collector telescopes<br>– Use SIRTF or NGST technology for lightweight optics<br>• Minimal component-level concerns<br>• Exploits existing and continuing technology<br>– SIM, Palomar, Keck, MMT, LBTI, SIRTF, NGST<br>• Extendable to future ultra-high resolution observatories | **<u>"Book" Concept</u>**<br>• Requires precision formation flying<br>– including line of sight rotation<br>– Requires precision spacecraft-to spacecraft metrology and communications<br>• 40K operating temperature<br>• Weight and volume may require additional launches<br>• Testing and verification complexity<br>• System and operational complexity |

# Major Strengths & Weaknesses: Hyper-Telescope

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June 7, 2002

| Strengths | Weaknesses |
|---|---|
| **Boeing-SVS Concept**<br>• Much less sensitive to exo-zodiacal light than Bracewell interferometry (Q≈1)<br>• Densified pupil eliminates "fixed baseline problem" of Bracewell-type interferometers<br>• Imaging capability directly applicable for high resolution astrophysics<br>• Precursor to future ultra-high resolution observatories | **Boeing-SVS Concept**<br>• Complex optical design, not as mature as the other options and all issues may not have been identified<br>• Long (100m) connecting structure<br>• Multiple launches required (3 estimated)<br>• In-space assembly either by astronauts or robotics<br>  – Transfer to operational orbit<br>• Tight beam alignment tolerances and/or controls<br>• Testing and verification complexity<br>• System complexity |

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# Strawman Process for NASA/ESA Collaboration